Application of Bioengineering to Slope Stabilization in Sri Lanka with Special Reference to Badulla District

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Abstract

Bioengineering is the application of engineering technology to biological systems or vice versa. It includes the use of vegetation in engineering layout to protect natural terrain and man-made systems from slope failure and soil erosion issues. The objective of this research is to explore suitable bioengineering plants and their use for slope stabilization in Sri Lanka, instead of using a non-ecological solution such as concrete. According to the research results, most of the sites were excavated in well graded clay soil types, and had slopes greater than 45°, which had a higher tendency to fail. However, by applying bioengineering (the use of vegetation) they were much more stable. After analysis of morphological traits of plants and their suitability for geotechnical applications, several native plants were chosen as suitable for use in slope stabilization projects using bioengineering in Sri Lanka.

Key words: *Bioengineering, slope stabilization, soil erosion, factor of safety, Sri Lanka*

1.0 Introduction

Bioengineering is the application of engineering technology to biological systems or vice versa. In this case it refers to the combination of biological, mechanical, and ecological techniques to reduce or manipulate erosion, preserve soil, and stabilize slopes using vegetation or a combination of living things, such as plants, and non-living materials. Plant roots increase the slope stability by holding soil particles together and decreasing soil erosion. The tensile strength of the roots is an important factor in soil reinforcement and slope stabilization (Lewis et al. 2001, Zhang et al, 2014)

2.0 Objective

The objective of this research is to identify plants which increase soil stabilization in Sri Lanka. Badulla district was selected due to the presence of severe erosion and the abundance and frequency of landslides. Additionally, there are many slopes in the district that could be expected to fail, but because of a dense vegetation cover have been stable. Observations suggest that certain plant species might be effective alternatives to non-ecological engineered solutions for slope stabilization.

3.0 Theoretical Considerations and Empirical Evidence

Conventional methods for slope stabilization have drawbacks such as unsightliness and higher cost. Therefore, alternative methods, such as soil nailing and soil bioengineering, for stabilizing slopes warrant investigation.

3.1 Factors Determining Slope Stability and the Factor of Safety

Slope stability is ultimately determined by two factors: the angle of the slope and the strength of the materials underlying it, Figure 1 from Steven (2014) shows how the component of gravity in the direction normal to the slope decreases, and the shear component (directed parallel to the slope) increases as the steepness of the slope increases. In (a) the shear

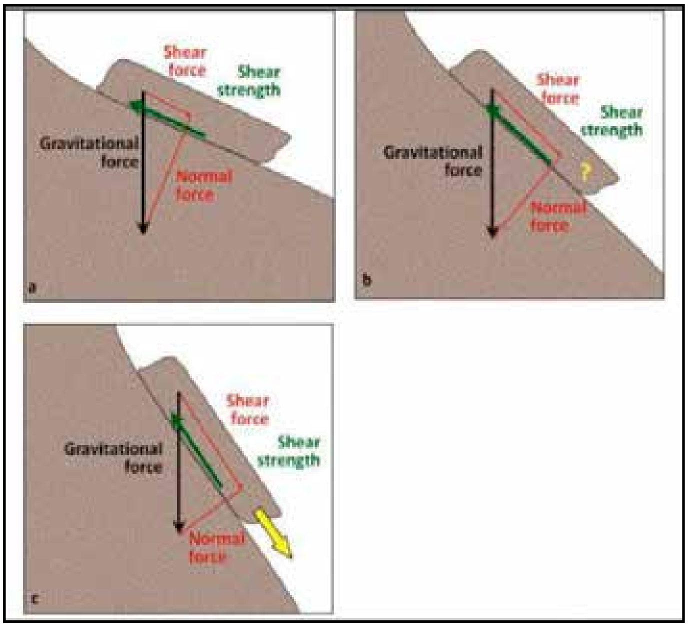

Figure 1: Differences in the shear and normal components of the gravitational force on slopes with differing steepness. The gravitational force is the same in all three cases discussed in the text, (a) Stable, (b) Unstable, and (c) Failure.

force is substantially less than the shear strength, so the mass is stable. In (b) the shear force and shear strength are equal. Thus the mass may or may not move. In (c), the shear force is substantially greater than the shear strength and the mass is very likely to move (Steven, 2014).

A slope failure situation exists when resisting and driving forces are equal and the factor of safety equals 1. Erosion management is intended to provide slope stability to guard the face of the slope and to reinforce the slope underneath the surface by interlocking soil debris with a complex matrix of roots (Yam, 1978).

The stress–strain behavior of soil and rock was modeled using a Mohr–Coulomb model, in which the non-associated flow rule was used.

$$S = C + C_r + \sigma \tan Ø' \quad \text{......................} \textit{(i) (Li et al, 2016)}$$

Where S is Soil shear strength (kPa), C is Cohesion of soil (kPa), σ is Stress normal to shear plane (kPa), Ø' is Effective friction angle(°), C_r is additional cohesion due to plant roots (kPa).

Factor of safety (FoS) is a commonly used index to describe the stability of a slope. The factor is expressed by the ratio of the fully mobilized soil shear strength to the mobilized stress. FoS for an unsaturated root soil slope considering a unit area is given as:

$$FoS = \frac{C_s + C_r + (\gamma h \cos^2 \beta + W_t \cos \beta) \tan \Phi' - U_w \tan \Phi^b}{(\gamma h \cos \beta + W_t) \sin \beta}$$

..... *(ii)* *(Leung et al, 2015)*

Where C_s is the true soil cohesion, C_r is the root cohesion, γ is the unit weight of the rooted soil, h is the thickness of the sliding mass measuring from the ground surface, β is the slope gradient, W_t is the unit overburden due to the plants (kPa), Φ' is the effective soil friction angle, U_w is the soil matric suction value, $\tan \Phi^b$ indicates how the shear strength increases with increasing matric suction (Leung et al, 2015).

According to equations *(i)* and *(ii)*, when cohesion (C_r) due to the presence of plant roots increases, it causes the overall factor of safety to increase. When the shear stress is greater than the combination of forces maintaining the object on the slope, the object will move down-slope. If the shear stress overcomes the cohesion forces keeping the particles together, the particles will separate and move down-slope. The likelihood of down-slope movement increases with steeper slope angles which increase the shear stress, and by any factor that reduces the shear strength or frictional resistance. This is regularly expressed as the safety factor, the ratio of shear strength to shear stress. Shear strength consists of the forces keeping the material on the slope and encompasses the friction and cohesion forces binding the rock or soil together. If the safety factor becomes less than 1.0, slope failure is expected to occur (Steven, 2014)

3.2 Particle Size for Slope Stability

If the particles are well-sorted or well-rounded, or both, then cohesion is weak. Saturated sediments tend to be the weakest of all because the effective stress (Terzaghi, 1925) is lowered by the hydrostatic pressure of the water. When the material becomes saturated with water, the angle of repose is reduced to very small values and the material tends to flow like a fluid. This is due to the water flow between the grains and eliminates grain-to-grain frictional contact; and also reduces the interlocking potential (Stephen, 2013)

3.3 Engineering Functions of Vegetation

Vegetation stabilizes slopes in various ways: catching raindrops, armoring the soil surface, and reinforcing, supporting, anchoring, and draining the soil. Vegetation can be used to enhance slope balance in a number of ways; such as by mechanical reinforcement, controlling erosion, increasing the infiltration ratio, decreasing runoff, and soil moisture adjustment (Shrestha et al., 2012).

3.4 Beneficial Effects

The beneficial effects of vegetation on the mass balance of slopes are:

(1) Root reinforcement: roots automatically reinforce a soil via switch of shear strain inside the soil to tensile resistance inside the roots (Li et al, 2016)

(2) Soil moisture depletion: evapotranspiration and interception in the foliage can restrict buildup of tremendous pore water pressure,

(3) Buttressing and arching: anchored and embedded stems can act as buttress piles or arch abutments to counteract downslope shear forces,

(4) Surcharge: weight of plants can (in certain instances) increase balance through elevated confining (ordinary) pressure on the failure surface.

Table 1, from Barker (1995), details the advantages and disadvantages of various groups of plants for slope reinforcement based mainly on the density of the surface cover they provide, the depths of their roots systems, the cost of installation and of the maintenance required.

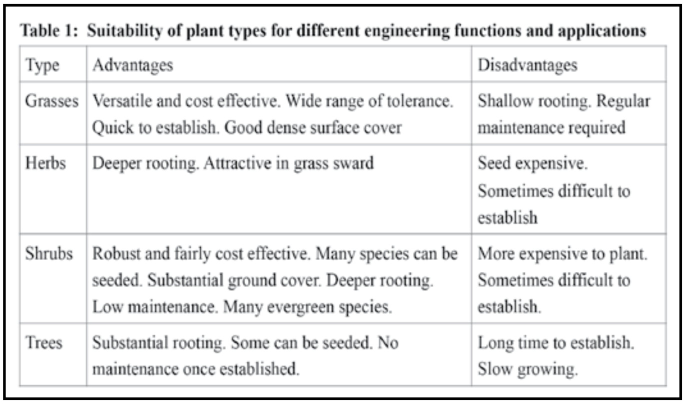

Table 1: Suitability of plant types for different engineering functions and applications

Type	Advantages	Disadvantages
Grasses	Versatile and cost effective. Wide range of tolerance. Quick to establish. Good dense surface cover	Shallow rooting. Regular maintenance required
Herbs	Deeper rooting. Attractive in grass sward	Seed expensive. Sometimes difficult to establish
Shrubs	Robust and fairly cost effective. Many species can be seeded. Substantial ground cover. Deeper rooting. Low maintenance. Many evergreen species.	More expensive to plant. Sometimes difficult to establish.
Trees	Substantial rooting. Some can be seeded. No maintenance once established.	Long time to establish. Slow growing.

Considering soil, bioengineering has advantages that rock and cement do not have. As an example, plant life can provide air pollutant uptake and carbon sequestration. Plants additionally offer visual benefits such as distraction screening, steering and navigation enhancement, and aesthetic pride (Lewis et al, 2001).

4.0 Materials and Methods

Literature study and field investigations were the main methods employed for the study. A few plants were previously recognized in the literature, based on past research on bioengineering applications in Sri Lanka. Using the Landslide Hazard Zonation Map provided by National Building Research Organization of Sri Lanka, fifteen sites of high hazard and medium hazard landslides on steep slopes in Badulla district were selected and investigated in the field, using ArcGIS 10.2 for compilation and analysis of results (Figure 2). Scientific identification of the plants and the description of specific morphological characters were done in the laboratory as was geotechnical analysis of soil (i.e. Sieve analysis) to select the most suitable plants for bioengineering purposes.

5.0 Results

Most of the selected slopes were steep slopes (Slope angle >45˚). It was observed that their steepness increased with the altitude. Soil types in the selected slopes were clay, silty, and sandy clay loam etc. They contained a considerable amount of moisture. Clay and clay-bearing soil types have a higher tendency to slip. In addition, the water content in the soil in the Badulla area increases during the local rainy season from September-February. Sieve analysis showed that most of the soil types were well graded, the constituent grains being equal in both size and shape. This allows greater soil porosity, which increases instability as previously discussed. Thus, the selected areas have a high tendency to slip and the slopes are unstable due to soil type and sorting. The locations of the slopes studied, their steepness, and the soil type and grading are given in Table 2 on page 49: In Figure 2 and Table 2 coordinates are given in decimal degrees to three decimal places (i.e. to the nearest 100 m on the ground).

Fig. 2: Site selection map: base map courtesy of Google Earth, overlay created in ArcGIS 10.2

5.1 Ground Covers and Soil Stabilizers

5.1.1 Clay Loam, Sandy Loam and Sandy Clay Loam

Lunularia cruciate, Sporobolus heterolepis, Poa labillardierei (tussock grass), *Miscanthus sinensis, Gleichenia linearis, Asplenium sessilifolium, Pteridium aquilinum, Desmodium heterophyllum, Desmodium* Sp., *Blooming Nelu (Strobilanthes* Sp.*), Lamiaceae* Sp., *Imperata cylindrical, Digitaria sanguinalis, Hemerocallis fulva* (Day lilies), *Ageratina riparia, Lamiaceae* Sp. & *Austroeupatorium inulifolium* were observed in the field to support slope stabilization, erosion control, and water infiltration. Their roots can reach moisture at greater depths than other grasses and annual vegetation during seasonal or climatic droughts. They have fibrous root systems which bind soil particles and increase soil cohesion, and thus shear strength of the soil mass helps protect against slope failures. Also, the dense growth of these plants makes a massive ground cover, forming a canopy which prevents high velocity impacts of raindrops against soil, causing soil debris to crumble and compact, reducing infiltration capacity, and leading to erosion by overland flow. Additionally, the deep roots remove water from soil; and therefore, they are suitable for preventing soil erosion slope failures.

Juncus prismatocarpus, Juncus usitatus, *Mimosa pudica* & *Arachis pintoi* were identified mostly in sandy loam and sandy clay loam. *Mimosa pudica* & *Arachis pintoi* spread via rhizomes that produce long tap roots at the nodes. They grow in most well-drained soil and are rather drought tolerant once established, making them additionally appropriate for dry, sandy regions. Properly installed plants can be difficult to eradicate due to the deep developing roots. The root system causes an increase in soil cohesion due to the covering behavior of the plant which lessens water infiltration and strongly decreases saturation during rainy seasons.

Digitaria sanguinalis, like other Poacea (grass) species makes a ground cover which reduces water penetration into the soil, and it prevents soil being heavily saturated during rainy periods. This plant has a fibrous root system which binds soil particles and increases cohesion of soil. The leaves of *Digitaria sanguinalis* have a hairy upper surface which causes water to drain downwards. Therefore, this plant can be applied to a bioengineering slope stability solution.

5.1.2 Silty Clay, Clay and Clay Loam

Bouteloua dactyloides, Wedelia trilobata, and *Microstegium vimineum* were identified for this study. These plants grow well in wet, well-drained, fertile soils, clays, sands or loams and might tolerate saline soils. They form an excellent, dense ground cover. These species are excellent for erosion control on slopes, banks and soil retention by roots and the stems come in contact with the soil. They prevent water infiltration and promote downward drainage of water; therefore, soil water absorption decreases. The extensive root system holds the soil at a higher strength, which increases soil cohesion.

Bouteloua dactyloides develops numerous fine roots that are tough and wiry, penetrating into the soil 4 to 6 inches, and strongly bind the soil particles.

5.2 Anchors

5.2.1 Clay Loam, Sandy Clay and Sandy Loam

Indocalamus tessellatus, Bambusa guangxiensis, Ochlandra stridula, Aundinaria densifolia, Bamboo types and *Osbeckia octandra, Osbeckia lanata, Osbeckia parvifolia* and *Artemisia argyi* were identified for this study. Bamboo roots are thin and fibrous and can penetrate 2-3 feet into the slope. The rhizome, which is the part of the plant that actually spreads, usually stays fairly shallow, less than 12 inches. The underground root system of bamboo is very similar to that of the culm. It can be described as an underground culm growing horizontally in the soil. This underground culm is the rhizome. All bamboo plants come under Poaceae family. For soil erosion prevention and slope stabilization these bamboo roots play a major role with increasing cohesion. Osbeckia plants' tap root and finer roots

Table 2: Soil Type, Slope Angle and Soil Grading in Selected Locations

Location Number	Coordinates of the Location (Lat., Long.)	Soil Type	Slope Angle (°)	soil type
L1	7.402, 80.999	Sandy Loam	>45	Well Graded
L2	7.265, 81.018	Silty Clay	40	Well Graded
L3	7.051, 81.123	Silty Clay	35-40	Poorly Graded
L4	7.105, 81.004	Silty Clay	30	Well Graded
L5	7.040, 81.016	Silty Clay	40	Well Graded
L6	7.083, 81.178	Clay	45	Well Graded
L7	6.931, 81.201	Sandy Loam	55-60	Well Graded
L8	6.893, 81.154	Sandy Clay Loam	65	Well Graded
L9	6.801, 81.021	Silty Clay	35-40	Well Graded
L10	6.764, 80.911	Silty Clay	45	Well Graded
L11	6.7586, 80.939	Clay Loam	35	Well Graded
L12	6.749, 80.858	Silty Clay	45	Poorly Graded
L13	6.747, 81.058	Clay Loam	35	Well Graded
L14	6.726, 81.004	Clay Loam	40	Well Graded
L15	Horton Plains	Clay Loam		

strongly bind the soil particles. The tap root has the strength to bind the soil and increase the cohesion to some depth.

5.2.2 Sandy Clay Loam

Calliandra calothyrsus is a fast-growing tropical tree. It prevents the soil erosion encountered in deforested areas. Its rooting system is composed of deep tap roots as well as lateral roots that enhance good soil structure (CABI, 2017). It is effective for soil erosion control. Additionally, it has strong potential for anchoring soil by way of deep roots, so it reduces soil mass failures, consequently increasing soil stability. *Calliandra calothyrsus* protects soil with the aid of decreasing runoff on a steep (35% to 60%) slope (Ashish et al., 2005).

5.2.3 Silty Clay and Clay Loam

Agave, Chrysopogon zizanioides (Vetiver), & *Cymbopogon nardus* were identified for this study. Agave has a complex root system that reduces soil moisture and strongly binds the soil particles. It thus reduces the water content in soil and acts as a ground cover. The agave root system, which includes a network of shallow rhizomes, is designed to help the agave efficiently seize moisture from rain, condensation, and dew. *Chrysopogon zizanioides* (Vetiver), & *Cymbopogon nardus* reduces the speed of the subsurface flows, reducing the erosion process and avoiding the activation of the landslide process. Further, where rock is fractured underneath, Vetiver will work as anchors. Vetiver, as a natural soil nail, binds the soil particles together as soon as it is established. It increases the shear strength of the soil thereby preventing it from sliding or slumping (Eboli, et al., 2011, & CABI, 2017)

Adenanthera pavonina has a very strong tap root and fine roots. The tap root penetrates deep into the soil and binds it strongly. It grows into a large tree and has a considerable evapotranspiration. It reduces water content in soil, which is especially important in the rainy seasons.

5.3 Anchors and Evaporators

5.3.1 Silty Clay and Clay Loam

The plants identified are *Gliricidia sepium*, and *Paspalum dilatatum*. *G. Sepium* are a fast-growing early succession plant species that take advantage of slash-and-burn practices in its native variety. It has a considerable evaporation and it reduces the water content in soil by evapotranspiration. In addition, it has a robust root system which binds soil very strongly. The strong tap root can go through fractures inside the rocks and anchor the root to the soil or rock particles; and for soil erosion, it has widely spreading roots. With them it increases the cohesion of soil so that the shear strength increases. It has good propagation methods, and less maintenance is needed. This plant has a high value in bioengineering applications. *Paspalum dilatatum* plants also act as a soil stabilizer with their rhizome and widespread fine roots. With the deep root system, they increase cohesion and remove a considerable amount of water by evapotranspiration (IEWF, 2017)

5.3.2 Trees in Clay Loam and Sandy Clay Loam

Rhododendron arboreum, & *Symbplocus sp. Rhododendron* is an important genus growing at high altitudes. Rhododendrons grow well in free, open, well-aerated, acidic soil with lots of humus to retain moisture. Rhododendrons also help in preventing soil erosion on the steep slopes of high altitude regions. The plants have a strong root system that can go through rock fractures and thus has a high anchoring potential. Hair roots increase the soil cohesion and the shear strength, which prevents erosion. Additionally, it has large leaves which evaporate large quantities of water, thus decreasing soil moisture content (Ashish et al., 2005).

5.4 Trees that Prevent Soil Erosion Using the Fallen Leaves or Needles as a Soil Cover

5.4.1 Clay Soil

Pinus roxburghii needles and *Syncarpia glomulifera* leaves act as a ground cover. When raindrops fall directly onto the soil floor without first being intercepted via plants or other materials at the soil floor, the strength of the raindrops may additionally disintegrate soil aggregates into small debris.

6.0 Conclusions

Imperata cylindrica, Mimosa pudica, Wedelia trilobata, Bouteloua dactyloides, Arachis pintoi (see Figure 3 above), *Gleichenia linearis* (see Figure 4), *Desmodium* Sp, *Microstegium vimineum, Digitaria sanguinalis, Lunularia*

Figure 3: Dense ground cover of Arachis pintoi (Location 12)

cruciate, Sporobolus heterolepis, Asplenium sessilifolium, Miscanthus sinensis, Goose Grass, Tussock grass, *Strobilanthes*, Blooming Nelu, and *Pteridium aquilinum, Bouteloua dactyloides, Juncus prismatocarpus, Ageratina riparia, Hemerocallis fulva, Lamiaceae, Austroeupatorium inulifolium, Ageratina riparia, Osbeckia octandra, Ageva, Chrysopogon zizanioides, Artemisia argyi, Cymbopogon nardus , Adenanthera pavonina , Calliandra, Juncus usitatus, Juncus prismatocarpus, Indocalamus, Oclandra, Osbeckia lanata*, Dwarf Bamboo species, *A. densifolia, Gliricidia sepium, Paspalum dilatatum, Rhododendron arboreum*, and *Symbplocus* Sp were chosen as bioengineering applicable plants in Sri Lanka. These plants will be planted in unstable slopes in the future in Sri Lanka, in order to prevent slope failures using the most suitable bioengineering methods for ideal locations. Using bioengineering avoids the use of unaesthetic concrete structures.

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Figure 4: Ground cover of Gleichenia linearis (Location 7)

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